Accretion in Strong Gravity: From Galactic to Supermassive Black Holes

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Abstract.
   The galactic black hole binary systems give an observational template showing how the accretion flow changes as a function of increasing mass accretion rate, or L/L_{Edd}. These data can be synthetised with theoretical models of the accretion flow to give a coherent picture of accretion in strong gravity, in which the major hard-soft spectral transition is triggered by a change in the nature and geometry of the inner accretion flow from a hot, optically thin plasma to a cool, optically thick accretion disc. However, a straightforward application of these models to AGN gives clear discrepancies in overall spectral shape. Either the underlying accretion model is wrong, despite its success in describing the Galactic systems and/or there is additional physics which breaks the simple scaling from stellar to supermassive black holes.

1. Introduction

The famous quote by John Wheeler that "Black holes have no hair" refers to their amazing simplicity. Theoretically they can be *completely* described by mass, spin and charge, while in any realistic astrophysical situation this reduces to simply mass and spin. However, black holes are most easily studied if they accrete, where the infalling material converts some of its immense gravitational potential energy to high energy radiation before disappearing forever below the event horizon. Thus there is another parameter which describes the appearance of the most easily observed black holes, namely their mass accretion rate.

   This theoretical simplicity is at first glance wildly at odds with the observed complexity of emission from accreting black holes. This is especially evident in the stellar mass black holes in our Galaxy (GBHC), where there is now a huge amount of high signal-to-noise data covering a large range of different mass accretion rates. However, recent progress has shown that these data can all be fit together into a coherent phenomenological framework, and that this can plausibly relate to physically based models of the accretion flow (Done & Gierliński 2003, hereafter DG03). The general picture emerging from the data is that the major hard-soft transition seen in the GBHC is consistent with being triggered by a change in the nature and geometry of the inner

accretion flow from a hot, optically thin, geometrically thick plasma to a cool, optically thick, geometrically thin disc (Poutanen et al 1997; Esin et al 1997).

Here we try to scale up the physical models of accretion which are so successful in describing the data from the Galactic black holes to the accreting supermassive black holes which power Active Galactic Nuclei (AGN) and Quasars. The goal is synthetise both theory and observations, to build a physically based model which can explain the data from accretion flows onto all masses of black hole.

2. Galactic Black Hole Binary Systems

The GBHC all have fairly similar mass, but show a wide variety of mass accretion rates due to the disc instability (King & Ritter 1998). These data give a observational template showing how the accretion flow varies as a function of (predominantly) mass accretion rate i.e. L/L_{Edd}. The standard disc models predict a very robust quasi-blackbody spectrum, with temperature $kT_{disc} \sim 1(M/M_\odot)^{-1/4}(L/L_{Edd})^{1/4}$ keV i.e. ~ 1 keV for a $10 M_\odot$ GBHC accreting at the Eddington limit. Such spectra are seen, but are generally accompanied by a weak (ultrasoft state: US), moderate (high state: HS) or strong (very high state: VHS) X-ray tail to higher energies. Together these form the soft states, which are seen at high L/L_{Edd}. However, at low L/L_{Edd} these objects can also show spectra which look entirely unlike a disk, peaking instead at ~ 100 keV (low/hard states: LS). Fig. 1a shows representative spectra from all these GBH states (e.g. the review by Tanaka & Lewin 1995).

To produce any emission at energies substantially higher than that of the disk *requires* that some fraction of the gravitational energy is dissipated in regions which are optically thin, so that a few electrons gain a large fraction of the energy. These energetic electrons can produce hard X-rays by Compton upscattering lower energy photons, and the shape of this spectrum is determined by the ratio of power in the hot electrons to that in the seed photons illuminating them, $\mathcal{L}_h/\mathcal{L}_s$.

While such Comptonization models can explain the broad band spectral shapes, they do not address the underlying problem of the *physical origin* of the hot electrons, or indeed the range $\mathcal{L}_h/\mathcal{L}_s$ required to produce the very different spectra shown in Fig. 1a. We can get some insight into these more fundamental issues from recent advances in understanding the physical nature of the accretion disc viscosity as a magnetic dynamo (Balbus & Hawley 1991). Numerical simulations show that any seed magnetic field can be continuously amplified by the differential rotation of the disc material, and dissipated through
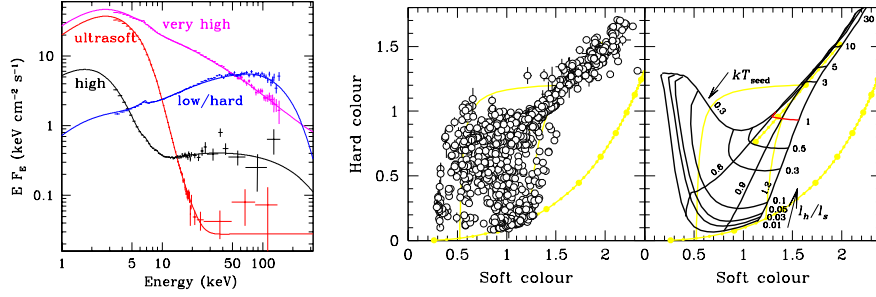
Figure 1. The left panel shows RXTE PCA and HEXTE data from XTE J1550-564 to illustrate the range of spectral shapes seen from the GBH. The middle panel compresses all the spectral information into colours, with soft and hard colours roughly related to the inverse of the mean spectral slope between 3–6 keV and 6–16 keV, respectively. All the black holes are consistent with the same behaviour. The right panel shows that this behaviour can be reproduced using Comptonisation models constrained by the sketched geometries shown in Fig. 2.

reconnection events. Including radiative cooling gives an accretion disc structure which bears some resemblance to the standard accretion disc models, but with some of the magnetic reconnection occurring above the disc as magnetic field loops buoyantly rise to the surface, reconnecting above the bulk of the material in an optically thin environment (e.g. Turner 2004).

However, these physical viscosity simulations also show that an alternative, *non-disc* solution can exist, where the whole accretion flow is optically thin, so cannot efficiently cool. The accretion flow forms a hot, geometrically thick structure, qualitatively similar to the Advection Dominated Accretion Flows (Narayan & Yi 1995), but considerably more complex in detail, with convection (e.g. Igumenshchev et al 2003) and outflows (Blandford & Begelman 1999) as well as advection (Hawley & Balbus 2002).

The existence of two very different accretion flow structures gives a very natural explanation for the two very different types of spectra (hard and soft) seen from the GBH. At low L/L_{Edd} the inner optically thick disk is replaced by an optically thin flow. There are few photons from the disk which illuminate the flow, so $\mathcal{L}_h/\mathcal{L}_s \gg 1$ and the Comptonised spectra are hard. When the mass accretion rate increases, the flow becomes optically thick, and collapses into an SS disk. The dramatic increase in disk flux drives the hard-soft state transition (Esin et al 1997). A weak tail on the dominant disk emission can be produced by occasional magnetic field loops buoyantly rising to the surface, reconnecting above the bulk of the material in an optically thin environment (US). Increasing the ratio of power dissipated above the
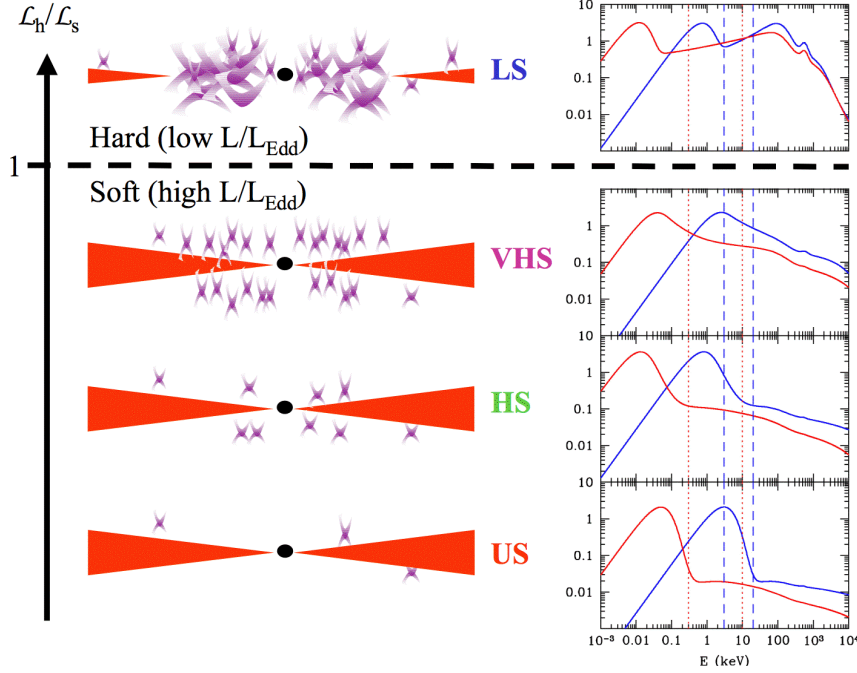
Figure 2. Sketched geometries corresponding to the spectral states, together with the EQPAIR spectra for GBH (higher disc temperature) and AGN (lower disc temperature). The dashed and dotted vertical lines on the spectral panels show the energy ranges for *RXTE* and *XMM-Newton*, respectively

surface to that in the disk increases $\mathcal{L}_h/\mathcal{L}_s$, increasing the importance of the hard X-ray tail. However, the *geometry* of the soft states sets a limit to $\mathcal{L}_h/\mathcal{L}_s$. Flares *above* a disk illuminate the disk surface, where some fraction are absorbed and thermalised. This adds to the intrinsic disk emission, fixing $\mathcal{L}_h/\mathcal{L}_s \lesssim 1$ in the limit where the flares cover most of the disk surface (Haardt & Maraschi 1993), which always results in a soft Comptonised spectrum, forming a power law with energy index $\alpha \gtrsim 1$ (VHS). Fig. 2 illustrates the geometries inferred for each state.

3. Quantative models of the X-ray spectra of GBH

The picture developed above for the geometry of the accretion flow puts constraints on the expected emission. The energetic electrons in the optically thin regions can produce hard X-rays by Compton upscattering lower energy photons, and the shape of this spectrum is broadly determined by the ratio of power in the electrons to that in the seed photons illuminating them, $\mathcal{L}_h/\mathcal{L}_s$. However, the spectral shape of the Comptonised emission also depends to some lesser extent on the

details of the electron distribution (its optical depth and whether it is thermal, nonthermal, or has some more complex shape) and seed photons (temperature and spectrum).

Detailed modelling of individual spectra from GBH show that the X-ray emission in the low/hard state it is fairly well modelled by thermal Comptonisation of accretion disc photons by hot, thermal (~ 100 keV) electrons (e.g. Gierliński et al. 1997), although there may be some evidence for non-thermal electrons also being present (McConnell et al 2002). However, in the soft states the spectral curvature in the tail is clearly best described by a combination of low temperature thermal (~ 10 keV) *and* nonthermal electrons (Gierlinski et al 1999; Zdziarski et al. 2001; Frontera et al. 2001; McConnell et al 2002; Gierliński & Done 2003; Kubota & Done 2004). These could be two physically (and perhaps spatially) distinct populations, or a single 'hybrid' plasma. The latter idea comes from the fact that even a purely non-thermal acceleration process cannot give rise to a completely power law electron distribution as electron-electron collisions will always give rise to *some* thermalisation at the lowest energies (Coppi 1999). Alternatively, even assuming that the energy injection to the electrons is purely thermal leads to a non-thermal tail from stochastic scattering (second order Fermi processes) on magnetic field inhomogeneities (Dermer, Miller & Li 1996; Liu, Petrosian & Melia 2004). Thus it seems very likely that the electron distribution is indeed complex, even if we are dealing with a single acceleration region.

Thus the simplest model for the emission is one where there is a single acceleration process for the magnetic reconnection irrespective of its spatial location (hot inner flow or flares above a disc). We use the sophisticated Comptonization code, EQPAIR (Coppi 1999) to translate this schematic picture into a *quantitative* model. The key advantage of this code is that it does not assume a steady state electron distribution, rather it *calculates* it by balancing heating (injection of power $\mathcal{L}_h$ into thermal and/or non-thermal electrons) and cooling processes (Compton cooling, which depends on $\mathcal{L}_s$, Coulomb collisions, photon-photon collisions leading to $e^{+/-}$ pair production and annihilation). The resulting spectrum depends primarily on $\mathcal{L}_h/\mathcal{L}_s$, i.e. on the geometry, and on the form of the electron injection. Guided by the results from detailed fits to individual spectra, we choose a constant electron injection spectrum which has optical depth of unity, with the power split equally between non-thermal (power law of $\Gamma_{inj} = 2.5$ up to maximum Lorentz factor of 10^3) and thermal components.

Fig. 1c shows a grid of colours resulting from the EQPAIR code for $\mathcal{L}_h/\mathcal{L}_s$ changing from 30 (top right of the diagonal branch) – 0.01 (softest hard colours), assuming seed photons from the disc at 0.3 –
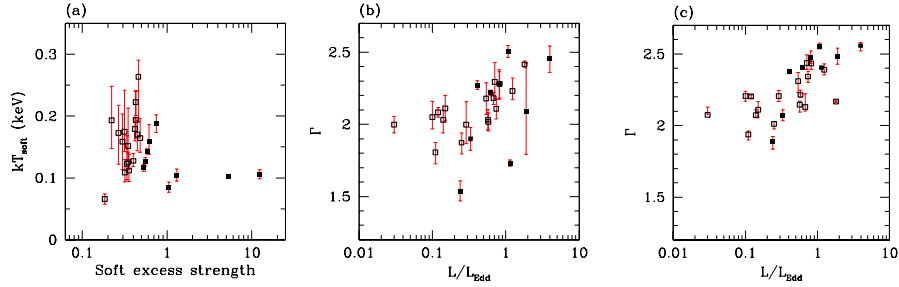
Figure 3. Panel (a) shows the soft excess strength versus its temperature. All the PG quasars used here have very similar temperatures despite large differences in mass and mass accretion rate. Panel (b) shows the power law spectral index inferred from fits including a soft excess. Several objects have high mass accretion rates but rather hard spectra, in conflict with the behaviour of GBH. Panel (c) shows this conflict is removed by using a model in which there is complex absorption from partially ionized material with a range of velocities along the line of sight (as expected from a wind from the inner disc).

1.2 keV as expected for the observed range in L/L_{Edd} for a standard disc. Changing only these two *physical* parameters can describe *all* the colour evolution seen from the GBH. These model spectra for each state are shown in the right hand panel of Fig. 2 darker line, with higher disc temperature), with the dotted lines showing the energy range of the PCA data over which the colours are measured (DG03). These *same* models for the accretion flow (both qualitative and quantitative) can also explain the very different colours seen from the disc accreting neutron star systems. These have similar gravitational fields, so should have similar accretion flows, but with the addition of a boundary layer between the flow and the solid surface (DG03).

4. Application to supermassive black holes

AGN accretion flows should be similar to those in GBH at the same L/L_{Edd}, except that the much larger mass black hole leads to a lower accretion disk temperature (Shakura & Sunyaev 1973). However, studying the AGN accretion flows is difficult as the black hole mass is much harder to determine, so giving large uncertainties on L/L_{Edd}. This problem can now be addressed using the recently discovered correlations of central black hole mass with the luminosity/velocity dispersion of the bulge, or the line width of the narrow line region, or reverberation mapping (e.g. Woo & Urry 2002). The other problem is signal-to-noise, with only the ~ 10 brightest AGN having adequate spectra in RXTE.

Again, this is now changing due to the unprecedented sensitivity of the EPIC camera (0.2–10 keV) on ESA's *XMM-Newton* satellite

If the models which describe the GBH spectra really do work then we can use the same code to *predict* what we should see from AGN, assuming that the *only* change in the accretion flow structure is due to the mass of the black hole changing the temperature of the disk. Since $kT_{disk} \propto M^{-1/4}$ for a given L/L_{Edd} then the GBH temperature range of 0.3–1.2 keV observed in the $10 M_\odot$ stellar black holes scales to 5–20 eV for a $10^8 M_\odot$ AGN. The grey lines in the spectral panels of Fig. 2 show the effect of this seed photon temperature change on the EQPAIR Comptonised spectra assuming the *same geometries* as used for the GBH.

The vertical lines on these spectra show the relevant bandpasses of the *RXTE* PCA (GBHC: dashed line) and *XMM-Newton* EPIC instruments (AGN: dotted), respectively. Plainly these models predict that the analogue of the soft states in AGN will have no direct disk emission in the XMM-Newton bandpass. The predicted spectra are approximately power laws, and soft excesses should be weak and rare. For all the states, the lower seed photon temperature means that the Comptonised spectra extend to lower energies and are slightly softer. Thus the soft state spectra always have Comptonised emission with $\alpha > 1$, and even the hard state spectra have $\alpha > 0.8$.

The bright quasar sample are objects selected by their strong blue/UV continuum flux, i.e. have a strong accretion disc component so should correspond to the soft state. This is confirmed by their estimated $L/L_{\rm Edd}$, with the majority spanning the range between $0.1 < L/L_{\rm Edd} < 1$. We selected all the publicly available (as of September 2003) X-ray spectra from *XMM-Newton* archive. We fit these 26 objects with a continuum model consisting of two Comptonized components. The hot component produces the power-law spectrum, while the cool one gives freedom to model any soft X-ray excess. Contrary to expectations, *all* the objects *require* a soft excess component. Fig 3a shows the characteristics of the soft excess for each object, plotting temperature against strength of the soft excess, $R_{\rm exc}$, measured by the ratio of unabsorbed 0.3–2 keV flux in the cool and hot components. The most striking property of the soft excess is its constancy in temperature. It is distributed in a very narrow range of values between 0.1 and 0.2 keV, and does not correlate in any way with the expected disc temperature estimated from black hole mass and L/L_{Edd}. Equally contrary to expectation is the spectral index of the hot Comptonisation component. Fig 3b shows this plotted against the estimated L/L_{Edd} for each object. While there is the same general trend as in the GBHC for high L/L_{Edd} objects to be steeper, there are several AGN which are at high Eddington fractions

which have $\alpha = \Gamma - 1 < 1$, and that many of these have strong soft
X-ray excesses ($R > 0.5$), denoted by filled symbols (Gierliński & Done
2004).

PG 1211+143 is the most extreme example of this in our sample.
It has $\alpha \sim 0.8$ for the intrinsic (reflection and ionised absorption cor-
rected) continuum, and also has a strong soft X-ray excess. Similar
objects are also seen in the literature, with the strongest soft excesses
often seen in Narrow Line Seyfert 1's (e.g. 1H 0419-577: Page et al
2002; 1H 0707-495: Fabian et al 2002). Plainly there are problems in
a simple application of the GBH spectral models to AGN. Either the
GBH models are wrong, or there are additional physical processes which
break the scaling between AGN and GBH.

5. Additional complexity in AGN spectra ?

One obvious candidate for additional complexity in the AGN spectra is
the generic presence of partially ionised absorption. The environment
around an AGN is often gas-rich, and X-ray illumination of distant
material such as the molecular torus can form a partially ionised wind
(Krolik & Kriss 2001). However, changes in this absorption on fairly
short timescales suggest that at least some component of this is directly
associated with the disk (e.g. Pounds et al 2003). The low disk tem-
perature in AGN means that most of the disk material has substantial
opacity from all elements except H and He. There are multiple line
transitions from these elements in the UV band, where the disk spectra
peak, so these can result in a strong line-driven wind from the disk. By
contrast, the higher disk temperature in GBH means the disk has much
lower opacity, predicting a much weaker wind (Proga & Kallman 2002).

The gratings on *XMM-Newton* and Chandra have shown the ionised
absorption in AGN in unprecedented detail. In general, multiple ab-
sorption components are seen, with different outflow velocities, columns
and ionisation states (e.g. Blustin et al. 2002). However, these absorbers
are included in the fits to PG 1211+143, and make no substantial dif-
ference to the size of soft excess or hardness of the 2–10 keV spectrum.
However, these absorption components are identified by their *narrow*
atomic features, implying that the dispersion in velocity along the line
of sight is rather small. This is *not* what is expected from the disc
wind described above. Instead this should be differentially rotating,
and outflowing, so has a very complex velocity structure which gives
substantial *broadening* (Murray & Chiang 1997).

We refit the data with a model in which there is only one Comp-
tonised component i.e. no additional soft excess, together with a simple

model of the absorption expected from a discwind (an ionised absorber convolved with a Gaussian velocity dispersion). Fig 3c shows the new distribution of spectral indices with L/L_{Edd}. *All* the AGN now have intrinsically steep spectra ($\alpha > 1$) as expected for the supermassive analogues of the soft state GBHC. The typical velocity dispersions are $\sim 0.1 - 0.3c$, as expected if the wind is launched from close to the last stable orbit of the disc, and the columns required are $\sim 10^{21-23}$ cm^{-2} (Gierliński & Done 2004). Such absorption models models can fit the data from individual bright objects as well as a separate soft excess component or ionised reflection (Sobolewska & Done 2004).

6. Conclusions

All the data from the galactic black hole binaries is consistent with showing the same spectral evolution as a function of increasing L/L_{Edd}. This evolution can be qualitatively modelled by a change in the nature and geometry of the accretion flow, from a hot, geometrically thick plasma to a cool, geometrically thin disc. The implications of this on the emitted spectrum can be quantified using sophisticated Comptonisation codes, and these can match the observed data. These models, with the addition of a boundary layer, can also explain the rather different spectral evolution seen from the disc accretion neutron star binary systems.

The Comptonisation models can easily be scaled up to *predict* the spectra from AGN and quasars, assuming that the physics of the accretion flow is the same. However, these predictions conflict with the observed spectra of the PG quasar sample. These all have high L/L_{Edd} so should be soft state analogues of the GBHC, but several have rather hard 2–10 keV spectra, and all require an additional soft X-ray component which has no obvious counterpart in the GBHC. Instead we suggest that these spectra *are* as predicted by the models, but that our view of them is distorted by complex, partially ionised absorption from an accretion disc wind. The large velocity shifts in the wind smear the intrinsically narrow absorption features so that the material gives no clearly identifiable signal in high resolution grating data. The difference between the GBHC and AGN is then that the AGN have strong absorption from a discwind, while the GBHC do not. This can easily be explained by the much lower disc temperature expected in supermassive black holes. Firstly this means that the disc itself retains substantial opacity, so there is much more line driving force for launching the wind, and secondly, heavy elements in the wind are less likely to be completely ionised, so have more effect on the X-ray spectrum. While such models

are speculative, the alternative is that we missing some substantial piece of accretion physics in the galactic black hole models.

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